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COMPUTER-AIDED DECISION-MAKING FOR FLIGHT OPERATIONS

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COMPUTER-AIDED DECISION-MAKING FOR FLIGHT OPERATIONS

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PREAMBLE

In this report we document the findings of a study relating to the assessment of various approaches to automation of flight operations, their impact on pilot workload and safety. The study was conducted jointly by staff of the Coordinated Science Laboratory and the Aviation Research Laboratory, both of the University of Illinois at Urbana-Champaign. Main contributors to this effort include R. T. Chien, P. Fitzhenry, D. Waltz, R. Hoolko, C. Jacobus, K. Hoover, D. Monck, D. Robins, P. Rutter, P. Satyanarayana, and T. Woo.

ON THE IMPORTANCE OF PROGRAM INTELLIGENCE

TO ADVANCED AUTOMATION IN FLIGHT OPERATIONS

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1. INTRODUCTION AND SUMMARY

1.1. Motivation and Scope of Study

In today's sophisticated aircraft, much emphasis has been placed on acquiring and displaying more and more complex information to the pilot. This trend has resulted in ever-increasing pilot workloads. Today's aircraft philosophy forces the pilot to evaluate a highly complex set of input data, decide upon a course of action, and then implement that action in minimal time. Such a situation is undesirable because it increases the margin of pilot error and lowers the probability of mission success.

A computer system, it is argued, can provide mathematically sound, evaluated decisions which could reduce pilot workload and pilot error. Thus automation of routine functions will be the answer for future systems. The pilot, it is stated, can then begin to function as system manager rather than system component. Unfortunately this seemingly straightforward reasoning does not apply to critical circumstances of high workload at which time the attention of a pilot must be given to numerous tasks. Conventional automation tends to present more data to the pilot and to require him to key in requests for specific information. Hence it tends to lower workloads during cruise and other similar lower workload periods; it tends to increase workload during critical times such as close combat. For example, while a scanning motion would normally give the pilot a general idea of what state his plane is in, a similar scan with time-shared display may require him to key-in several requests by hand, a task more difficult and time-consuming for him.

In order to provide lower workload all the time and more safety for the pilot and the system we feel it to be necessary to consider systems with program intelligence. Such systems can carry out optimum decision-making tasks according to preset guidelines under a variety of circumstances and therefore can provide lower workload and improve safety in flight operations.

The purpose of this project is to identify and develop techniques for automating a subset of crucial pilot tasks in flight operations. These specific techniques and a general design philosophy are to be programmed and demonstrated on our computer and simulation facilities at the University of Illinois. These techniques will then be considered by the U. S. Air Force for detailed investigation and development, and for possible adoptation in future avionic systems.

One important goal of the first phase of this project is to give an in-depth analysis of the various tasks involved in flight operations and to give an assessment of the present trends in automation, its promises and drawbacks. Specific attention is given to two studies which were recently done and reported in

(1) Integrated Information Presentation and Control System (IIPACS), Volume 1 through 4 by Staff of the Boeing Company, 1971.

(2) Study of the Information Management Aspects of Integrated Avionics (IMS), Volumes 1 and 2 by Bernard List, Texas Instruments, Incorporated.

A second major goal of the first phase of this project is to identify candidate tasks for potential automation and to provide an educated guess as to a possible schedule for such events to take place.

The study reported here took place during a three-month period starting in September of 1973. During the early days of this study it became clear that the assessment phase should take place only after a detailed analysis is done on each important task area of flight operations. The task areas were identified to be as follows:

1. Autopilot and Stability Augmentation
2. Fuel Management
3. Energy Management
4. Navigation
5. Degraded Mode Operation
6. Weapon Delivery

Detailed analysis of these areas are presented in Sections 2.1 through 2.6. Further comments are given in Section 2.7. A general appraisal is given in Sections 3.1 through 3.4. A description of some important characteristics of a fully-automated system is given in Sections 4.1 through 4.3. Concluding remarks and recommendations are given in Sections 5.1 and 5.2.

1.2. Summary of Assessment of IIPACS and IMS

This section is a summary of an appraisal by ARL/CSL of the IIPACS/IMS with respect to conventional aircraft systems and to systems using programmed intelligence beyond IIPACS/IMS.

In IIPACS and IMS, which are the baseline documents for this contract, is developed the concept that the pilot should be a manager with responsibility for high-order decisions. The pilot sets up Autopilot modes, flies the aircraft during transitions between modes or when a mode is not available which fits his current phase in the mission. Otherwise he is not required to actually fly the aircraft. The pilot has access to information bases such as fuel remaining, optimal energy management profiles, communications from a central controller, known failures within his aircraft system, current weapons available. The pilot brings these bases to bear upon the mission expectations and the pilot's past experience and training. The result is a plan or a set of procedures which the pilot sets up such as Autopilot modes or arming a weapon. Terms describing the tasks done by pilots in an IIPACS/IMS system are monitoring, target recognition, setting-up, keying-in, reading, interpreting, selecting, communicating, and eating.

IIPACS/IMS was designed to have a major impact on pilot workload and indeed they do. A large complement of aids are available to the pilot. Flight control is accomplished by direct pilot command of control surfaces or by six Autopilot modes. The pilot can choose one or more modes depending on whether they are conflicting or not. An example of conflicting modes are altitude hold and terrain following. The pilots' control authority over the aircraft has been reduced to gain stability augmentation and control harmonization. These are basic servo loop tasks the pilot performs in conventional aircraft. The system does not check for reasonableness of possible structural damage to the aircraft or entry of an unsafe flying mode.

The navigation system has a similar architecture. A variety of modes, namely, Doppler, inertial, and satellite, are offered which are appropriate in terms of accuracy and reliability for different phases of a mission. A concerted effort was made to automatically check whether a mode is operating and if it is not, to use the next best nav aid available. In the conventional system, the nav aids selection, fault detection and switching is basically the pilot's responsibility. To a large extent

IIPACS/IMS is a system with a very complex sensor or a set of sensors with complex rules for selection of an appropriate nav aid. IIPACS/IMS has automated nav aid selection based on what is most accurate and available. The data goes to map displays, command bar displays, and the Autopilot. In a system with programmed intelligence this represents a very useful data base and there are no glaring shortcomings with the IIPACS/IMS system.

IIPACS/IMS provides the pilot a large array of computed data displays, energy management, command bars, fire control symbology, which are more usable or concise than the raw data being operated on. This feature is lacking in scope on conventional aircraft where airborne computation power is restricted by current technology. IIPACS/IMS views energy management optimization of a flight profile with respect to time, fuel, range, or safety, as aids to pilot action in setting the aircraft throttle and attitude. The displays are basically graphical. The command bar displays are simpler and easier to interpret than the graphical types but are not as blunder proof. The fire control symbology is a form of a command bar display where missile capability, range to target, and optimal release point are computed and displayed. Lack of computed data displays requires the pilot to either perform the computation or sacrifice optimal performance and make decisions which have large tolerances for error. Weapons release may be consistantly done too close to target making the aircraft too vulnerable. Energy profiles may be stored in the pilot's head and used as deemed appropriate. These are crude approximations to what could be achieved by a computer using a large number of sensors, temperature, airspeed, aircraft weight, etc., and optimizing the profile to the specific condition or state of the aircraft.

Failure prediction, detection, and correction is incorporated in IIPACS/IMS. The aircraft components covered under this failure monitor do not have to be constantly monitored by the pilot, as in conventional aircraft systems. Nor does the pilot have to decode on its priority or on remedial actions. IIPACS/IMS does provide trending on certain major components using vibration or oil analysis as indicators. Many failure detections are left up to the pilot to find and he must be constantly monitoring the aircraft system for possible breakdowns. Actions to be taken on multiple failures are the pilot's decision in IIPACS/IMS. The conventional system automatic failure detection system is usually limited to critical components, such as control surface actuators.

As will happen when a radically new system is introduced, the workload in some areas will decrease but will increase in other areas. When the pilot is required to read text or key-in a request to the computer system, he is performing work not usually found in abundance in the cockpit. The capability of putting displays on any of 2 or 3 different displays is a great hedge against failure of a display, but can hinder finding information by looking at its home position on the cockpit. While some memorization has been reduced (e.g. by including optimal climb profiles in the information retrieval system) the procedure for operating the information retrieval system must itself be memorized.

A negative transfer of training from conventional aircraft systems to the IIPACS/IMS aircraft will be another pilot problem. Old reactions and routines no longer apply directly since the cockpit concept is so different.

The pilot is still the focal point during emergencies and combat maneuvers in IIPACS/IMS. These are high workload situations to begin with and these are the crucial areas for mission success. Even in the normal course of operations the pilot is required to do a lot of set-up, such as selecting, fusing, and sequencing a weapon. Display update rates on some of the computed displays are not real time. This decreases their value during combat, where high performance maneuvers are common.

What a system with programmed intelligence can offer beyond IIPACS/IMS is an alternate path that does not require pilot intervention for some decision making required in a fighter cockpit. A system with programmed intelligence has the potential for access to a larger information base than the pilot. In some forms of information processing, it can be much faster. Areas such as failure monitoring, energy management and flight safety, natural language communication between pilot and aircraft systems, and airborne flight planning are the most promising for early systems with programmed intelligence.

If pilot workload is to be reduced the computer system must be given some authority to control the aircraft system. This implies that the hardware linkages exist and the pilot is willing to delegate the authority. This will not be a total delegation in all cases since a system with programmed intelligence in the near future will not have capabilities the pilot has in the areas of pattern recognition and total natural language communication with the outside world.

1.3. Summary of Conclusion and Recommendations

The following is a summary of our conclusion and recommendations:

1. Conventional automation techniques as proposed in IIPACS/IMS are useful for many circumstances. Many of these techniques can be incorporated into aircrafts of the 1975-80 period,

although certain improvements should be made regarding the man-machine interface.

2. The current trend in computer hardware cost reduction will most likely continue. This fact plus the compactness of LSI technology will encourage the development of large scale data bases that will form the backbone of intelligent routines. By and large these systems can be constructed with conventional software. However, we believe the concepts of programmed intelligence should be employed to achieve better performance and to lay the proper foundation for the transition to baseline intelligent systems.
3. Many of the large data base intelligent routines eventually will be of the complexity of OS360. No simple formula can be used to describe the performance of a software system of this complexity. These systems must be open-ended and debuggable by sections. The only meaningful approach to the design of such systems is to set organization guidelines and to use a modular approach as much as possible. Thus the concepts of heterarchy, automatic deduction, and flexible control structure will be necessary.
4. The age of intelligent routines will definitely be the transitional period between conventional software organization and software organization with the AI approach. Both approaches will make extensive use of low-level software routines of conventional nature.

5. In order to spearhead the development of intelligent systems we propose to develop a prototype intelligent system with the capabilities to automatically

   (1) detect and predict failure;

   (2) operate in degraded modes; and

   (3) communicate at intelligent levels with man and machines.

   In order to demonstrate our accomplishments in realistic environments via computer simulation we also plan to carry out a number of subprojects including

   (4) the construction of a data base;

   (5) the development of a pseudo-natural language communications capability; and

   (6) the construction of failure model for diagnosis.

2. TASK ANALYSIS AND ASSESSMENT

2.1. Autopilot and Stability Augmentation

2.1.1. Introduction

The Autopilot does lower level computations and actuates the aircraft's control surfaces. For most purposes it can be considered as a feedback control mechanism capable of maintaining any one of several flight parameters. For example, the pilot may select parameters such as altitude or heading which the Autopilot will then maintain.

The Autopilot is discussed further in the sections covering energy management and navigation.

2.1.2. Conventional Autopilots

The Autopilot is probably the most automated subsystem in a conventional airplane. Currently, Autopilots are used primarily for those phases of a mission which do not represent high workload for the pilot, such as flying from home base to the target area. Most Autopilots in conventional aircraft are built as autonomous systems, i.e. They have only limited inputs from other subsystems, and computations are not performed in a central computer.

2.1.3. The IIPACS Autopilot

The IIPACS system provides six autopilot modes. Incompatible modes are disconnected automatically when the pilot selects a new mode.

1) Control stick steer--Autopilot has control of stick.
2) Navigation steer--navigation system supplies all commands.
3) Speed control--speed is keyed and held constant.

4) Altitude hold--altitude is keyed and held constant.

5) Automatic terrain following--displacement from ground set and held.

6) Automatic wing sweep--sweep angle is automatically set as a function of speed.

By providing many modes of automatic flight, the IIPACS system made itself very flexible. Since several modes are available, the pilot can choose whatever function he wants to be taken over by the computer. For instance, if he wants to delegate the function of controlling the speed without at the same time giving up heading control, he can do so by selecting the speed control mode. Similarly he can select several non-conflicting modes simultaneously.

In the IIPACS system the computational functions of the Autopilot and stability augmentation are performed in the central computer. The authors claim that the feedback sensors for the Autopilot are redundant enough to ensure safe flight. Single channel failure in the stability augmentation system is indicated by master caution flashing and readout on a MPD (multipurpose display); dual channel failure is indicated by master caution flashing, readout on a MPD and a voice warning. Whenever two or more channels fail to work the system suggests the best mode to the pilot and advises him to land as soon as possible.

2.1.4. Problems

One problem is the IIPACS system's inability to reject a command to the Autopilot if it is not a safe one. The Autopilot faithfully obeys any command it receives either externally from the pilot or internally from the navigation system. If the command is unsafe and given either by mistake or because of ignorance about the state of the aircraft, the system (either the Autopilot or some higher level decision maker) should reject that command and inform the pilot. For instance, an attempt to enter the altitude hold mode during a landing should be rejected. Similarly, attempts to maintain a collision course should be questioned.

The IIPACS Autopilot could be further expanded. Automatic take-off and landing capabilities (already available in some aircraft) were not considered in the IIPACS system.

2.1.5. DC-10 Performance and Failure Assessment Monitor

This system is an automatic landing system and monitor of the type postulated above. It provides a landing display that has the same landing queues as those described in the IIPACS navigation section displayed on the VSD (vertical situation display). The runway is traced and a cross is placed on the line drawing of the runway to indicate the projected point of contact. The system follows a radio beacon down to the runway, compensating for deviations due to environment or internal aircraft disturbances. The response of the aircraft is anticipated faster than real time via a generalized 4th order approximation of the aircraft system dynamics. These calculations are used to project aircraft glide path and are compared to actual response. If substantial deviation occurs the system calls for pilot assistance. This system promises to be extremely useful in low visibility conditions.

2.2. Fuel Management and CG Control

2.2.1. Introduction

Controlling fuel utilization is essential to aircraft performance and mission success. Minimizing fuel consumption can decrease the number of air refuels. Monitoring and predicting fuel consumption can eliminate the danger of running out of fuel.

CG (center of gravity) control refers to the shifting of fuel between tanks to alter or maintain the aircraft's center of gravity. CG control is essential to flight safety and aircraft maneuverability. Loss of CG control may lead to a stall, and makes landing and engine-out operation very dangerous.

It is not possible to totally isolate the fuel management and CG control functions from the other aircraft systems. Fuel management is a corollary function of navigation in that it both requires information from and supplies information to the navigation system. Similarly, CG control is a corollary function to the Autopilot, since a change in the flight mode may require a shift of the center of gravity. Fuel management and CG control can also be considered as part of energy management, since they both affect various energy envelopes. In this section, we will use the term fuel management to refer primarily to long term fuel usage. Short term fuel usage is covered in the energy management section.

2.2.2. Conventional Systems

The pilot has switches to select the tank used to supply a particular engine. He can also activate pumps to shift fuel between tanks, in order to change or maintain CG Position. Most computation and control is done by the pilot on all but a few conventional airplanes.

2.2.3. The IMS System

IMS contains a fairly complete discussion of fuel management, including detailed flowcharts and equations. Indeed, a fuel management program has been written in their recommended higher level language, TPL (about 200 lines of code), and an estimate of how often the program should be run has been made (about twice per second).

The IMS fuel management system monitors fuel use and gives the pilot planning and control information. As a planner, the system provides updates of the estimates in flight as the mission proceeds. As a control aid, the system computes power settings for optimum energy utilization, and presents these to the pilot. As a monitor, the system periodically checks the mission progress and fuel remaining. If the system detects a fuel emergency it alerts the pilot.

2.2.4. The IIPACS System

The IIPACS study does not have as detailed a discussion of fuel management and CG control as the IMS study. However, it does have a proposed layout for the display and control switches associated with these functions. This panel displays the total amount of fuel in each tank and the current center of gravity. In addition, a bar graph of fuel remaining displays: 1) the amount of fuel to reach target (by the preplanned route), 2) the amount needed to fly the remainder of the preplanned route, and 3) the amount required to return directly to home base from the present position. Simple switches allow for manual override and manual tank selection. The fuel dump switch and air refuel switch are also located here.

Fuel management and CG control are usually considered as fairly low level functions, and they are mostly "submerged" in the IIPACS and IMS layout of functions. Therefore they usually do not provide a high pilot workload in the proposed 1975/1980 airplane.

2.2.5. Problems

There are two cases where the pilot is still in the fuel management control loop. These are:

1. Major inflight changes to the flight plan, such as a change in route or destination. In these cases, it is clearly desirable for the fuel utilization to remain "hidden" as long as there is sufficient fuel for the new plan. This means that changes to the flight plan (stored in the computer and used by both the navigation and fuel management routines), should be allowed by the fuel management routines if the changes are possible. All that the pilot should have to know is what fuel will remain if he makes the proposed change, and perhaps, how the remaining fuel compares with the amounts in the original flight plan. Ideally, the navigation routines should not require the pilot to do anything but enter the new end points of the route change; in the IIPACS/IMS systems the pilot must also check whether the fuel remaining is reasonable for the proposed change.

2. Emergencies, i.e. when the airplane is going to run out of fuel. This would seem to be the situation where IIPACS is most in need of improvement. It is not at all clear that it is good, necessary, or sufficient to turn on a "bingo" light when fuel remaining is insufficient to return home. One problem is that the fuel management routines do not know what else is going on at the time the bingo light goes on (for example, the pilot may be making a landing or taking evasion measures and the light would be a serious distraction).

The problem of emergency procedures can be extended to a general criticism of IIPACS/IMS. There is no possible solution to this problem as long as the "operating system" that ties the functions together is either non-existant or inflexible. The IMS designers at least realized that having the CPU execute a simple circular list of jobs would not be adequate. To improve the handling of emergency procedures, one has to forego the simplistic idea that any system should be allowed to take over a display (and the pilot's attention) whenever it independently discovers an error or a dangerous situation. A higher level program must interpret requests for emergency actions by lower level programs with an understanding of the current environment and state of both the pilot and the airplane. One wants to resort to alarms as seldom as possible, not only to bother the pilot less, but also so he will be more likely to react to them properly. In the general case, the program should not assume its job is over once an emergency has been signalled, but rather it should check to make sure that corrective action is taken.

2.2.6. Summary

To summarize, fuel management and CG control are functions which are (in IIPACS/IMS type aircraft) almost completely automated. They are closely connected with the navigation/autopilot routines and take little CPU time. In normal situations the IIPACS/IMS systems are probably sufficiently flexible. They are invoked automatically to provide data base updates and also when needed to estimate and display how proposed course changes affect the fuel utilization. There is need for improvement in the handling of emergencies, but only major system redesign can provide satisfactory operation in emergency situations.

2.3. Energy Management

2.3.1. Introduction

The importance of having an effective energy management system aboard the Mach 2 fighter aircraft is apparent when its environment is considered. A maximum rate climb out can consume 50 percent of total aircraft fuel. Combat times are on the order of five minutes. A four second saving in time of an optimal manuever can make the difference between a successful intercept and the loss of a defended target. Given this fast, high stress environment, a system which will manage the aircraft energy optimally, monitor the energy state against safety envelopes, and, in general, reduce pilot workload will be a valuable aid to pilot performance and mission success.

Efficient use of energy requires a repertoire of optimal energy profiles. For instance a loiter would require a maximum endurance profile, intercept of another fighter minimum time climb profile. Other possible profiles include minimum fuel climb, minimum range climb, and maximum range cruise. Since a mission for a fighter consists of a series of subgoals, each with its own optimal profile, an optimal transistion from profile to profile is also needed.

To keep the aircraft energy state from leaving safety boundaries, be it from a pilot who is following an overly enthusiastic energy profile, or from one who is inattentive of an instrument, an energy state monitor is recommended. This monitor's function is to keep the aircraft from suffering structural damage from excessive G-load or airspeed, and from inadvertently entering a stall, spin or region of reversed command. Also this monitor should constantly check current energy capability against the energy needed to avoid external obstructions such as the ground or other aircraft.

The energy management system must reduce the pilot workload or its full potential capability will not be realized. If a pilot does not have the time to set up or interpret a mode of energy management he might as well not have it available. Energy management displays should present data in easily understood formats, with the amount of data displayed reduced to a minimum. Data formats could be the raw data, such as altitude or mach number, command bar displays, graphic displays, alphanumeric displays, control feel from yoke or stick, or auditory signals. Graphical formats and exception data displays, displaying data out of norm, are ways of reducing the amount of data shown to the pilot.

The energy management system should have the capability of directly driving the Autopilot, thus relieving the pilot from the job of closing the loop between energy management and aircraft controls. The pilot should have override capabilities on the Autopilot. The effect of his override can be displayed to him through exception data displays or control feel pressure on the stick.

A properly designed energy management system can both reduce pilot workload by helping him select the proper flight profile and improve aircraft performance. A poor system may improve performance in light workload periods, but not get used at all when it is needed most. The energy management system can display tradeoffs in time, fuel, and airspeed. Given an idea of what the impact of a profile will be, the pilot can reduce the uncertainty in selecting a profile. Decision making on a more global scale can also be aided by an energy management system since the computed tradeoffs can be used by other aircraft subsystems.

2.3.2. Conventional Approach to Energy Management

A good deal of the conventional energy management system resides within the pilot. He is trained on the ground what the general guidelines and tradeoffs are. He has a set of numbers and procedures memorized or available as checklists in the cockpit. When he desires a cruise speed he uses the one he has memorized. The pilot optimizes a parameter by making perturbations around the selected cruise speed and observing the effect on the variable to be optimized. He also memorizes the raw data boundaries of the safety envelope and checks these against the actual raw data, airspeed etc.

Airborne computer aids to the pilot are limited: simple calculation of steady-state time in air with remaining fuel is an example. The computer usually has some access to aircraft controls in the form of wing sweep angle and center of gravity location through fuel shifting.

Displays present raw data: altitude, airspeed, and attitudes. Some first order safety envelope violations are detected and alarms sounded to alert the pilot, and some processed data is presented to the pilot for his information, for example range or time to go before fuel is depleted.

Autopilot utilization is usually through the pilot. He selects altitudes and headings, sets up the Autopilot and transfers control to it. The pilot makes changes by resetting the Autopilot. This utilization of the Autopilot is separate from the link to it from the navigation system. The computer does control wing sweep angle and fuel location. Terrain avoidance systems operate under full computer control.

2.3.3. IIPACS/IMS Approach to Energy Management

IIPACS/IMS energy management systems start with ground training of the pilot, building on the training given pilots of conventional aircraft. Further instruction is given to the pilot on how to use displays which reflect an expanded computer-based energy management system. Some display types, command bars, dials, and alphanumeric displays, will be familiar to the pilot of conventional aircraft. However, the graphical display format will be a new cockpit display type for the pilot. The pilot must learn how to use the computer-aided energy management system with the ease and regularity that he uses the navigation system.

The IIPACS/IMS computer system is available as a storehouse of checklists and integrated displays with current air data parameters shown in relation to other aircraft numbers. The pilot is still required to know the aircraft numbers, stall speeds and other aircraft performance indices.

The IIPACS/IMS airborne computer aids are extensions of the conventional system. IIPACS does expand on the optimization of aircraft performance and energy state with respect to a safety envelope. This concept is called the integrated total energy management system (ITEMS). The computer system has access to real-time data on angle of attack, attitude, control surface deflections, G-load, thrust, static pressure, dynamic pressure, air temperature, altitude and other variables representing the changing conditions of flight. Given these inputs the computer develops schedules for flight profiles which are optimized with respect to minimum energy, minimum time, or maximum range and safe flight operating conditions. The pilot has access to these schedules through the cockpit displays and to some extent the energy management system can control the Autopilot directly.

The displays used by items are as follows:

On a primary display is the energy control director of ECD (Figure 1). It uses a variable size circle with variable rectangles inside of it. The ECD indicates to the pilot the necessary adjustments of pitch, roll, and longitudinal energy to stay with the necessary flight plan. Command bars are also on the display to indicate pitch, rate of pitch, roll, and rate of roll, and rate of roll to minimize energy expended.

The pilot can also call up three supplemental energy management displays for guidance on optimum settings of the aircraft controls and prediction on where the state of the aircraft will be in the near future. The first display is altitude vs. range (Figure 2). It includes a curve for minimum time climb to a predetermined position, one for maximum range climb, and a dot and arrow indicating the aircraft's present position, magnitude and direction of motion relative to the curves.

The second display is velocity vs. G-load (Figure 3). It graphs an envelope and the present position and direction of motion of the aircraft relative to the envelope. It presents to the pilot an indication of the aircraft approaching an unsafe flight condition relative to the plane's configuration and load conditions.

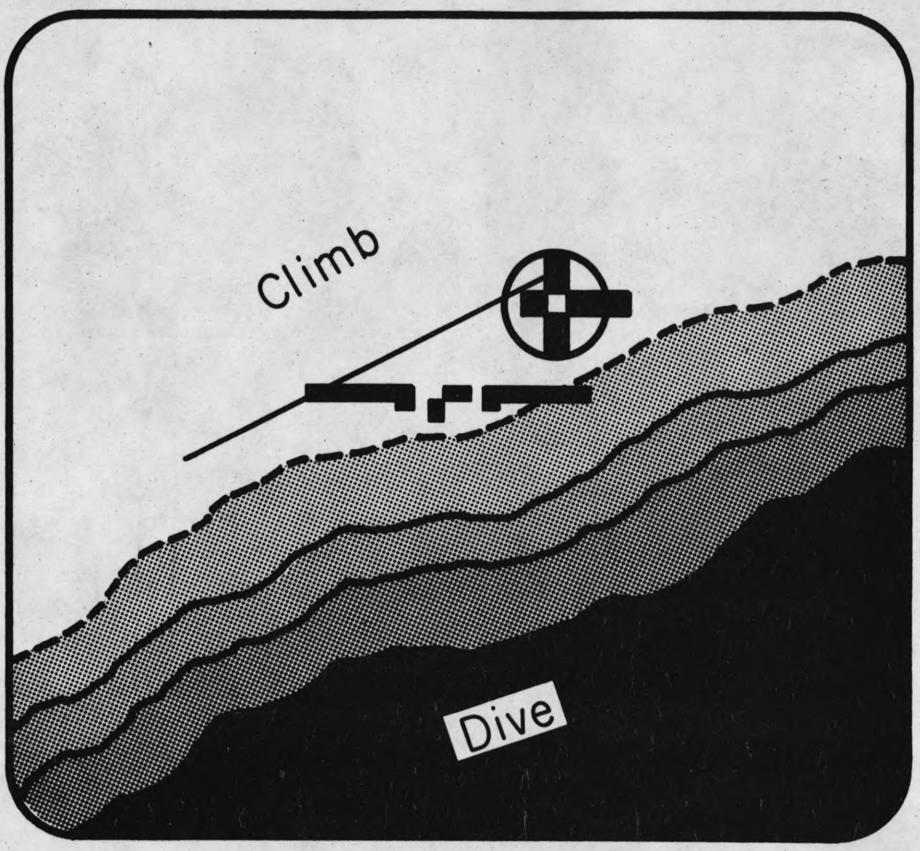

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Figure 1. Energy Control Director Display (ECD)

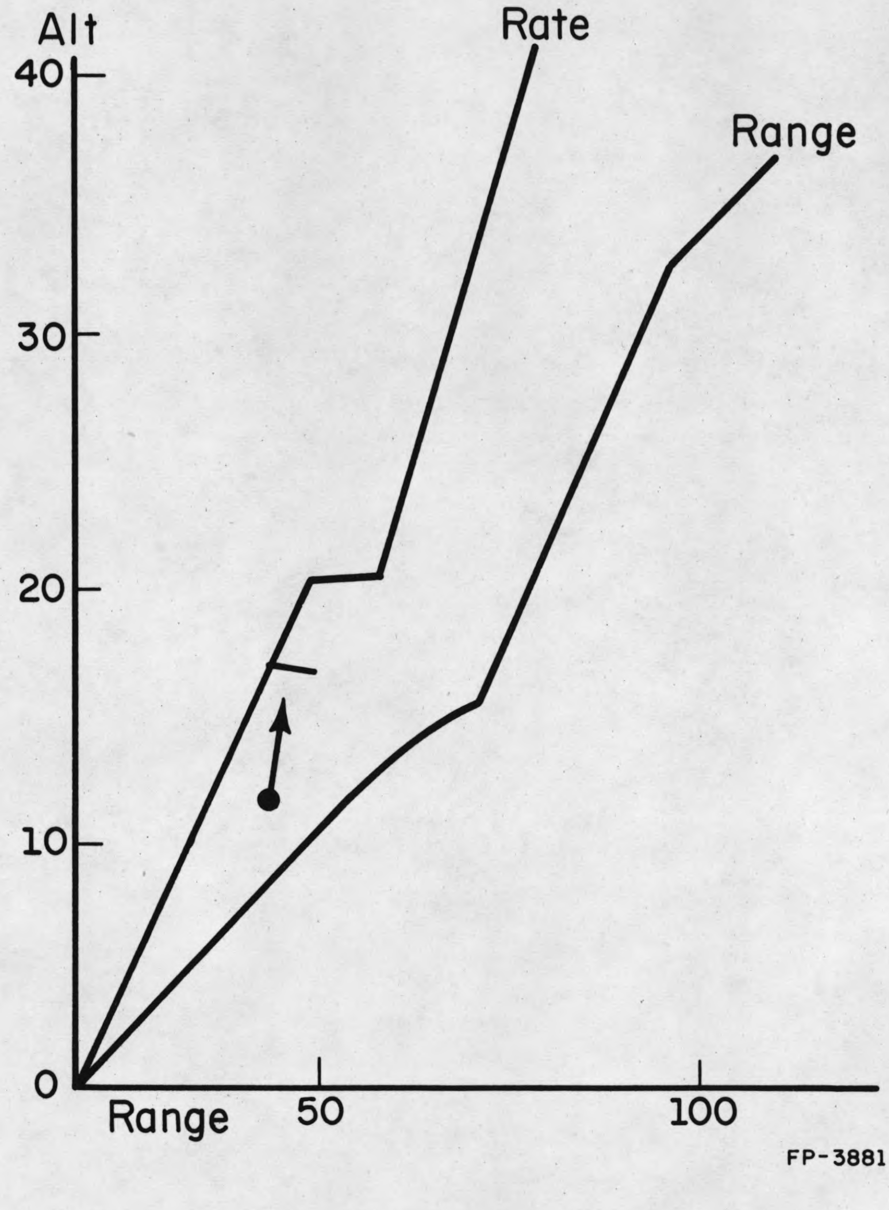

Figure 2. Optimization Display-Altitude vs. Range
The steeper curve indicates the maximum rate climb, and the other curve indicates the maximum range climb. The circle and arrow indicate current aircraft state.

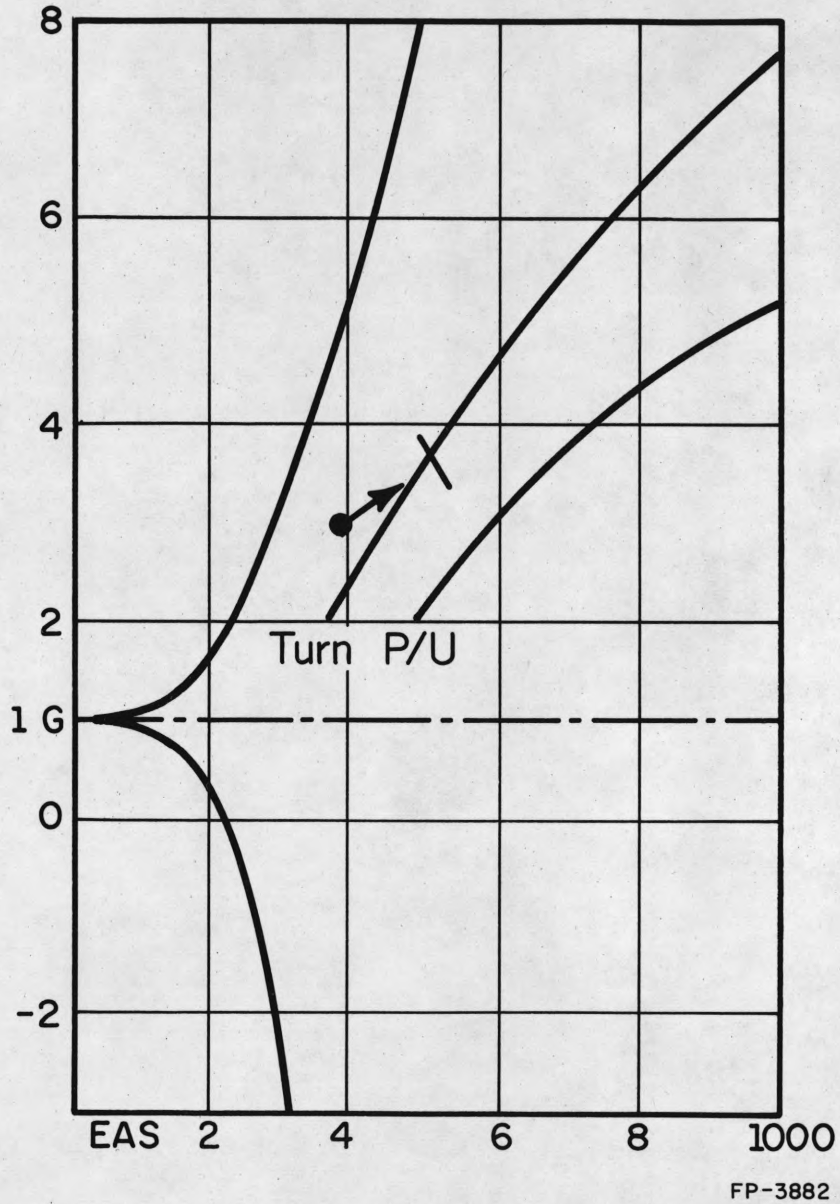

Figure 3. Velocity vs. G-load Envelope Display

The third display is thrust vs. airspeed (Figure 4). The two curves are: the total available thrust for a given altitude and airspeed, and the thrust required to maintain an airspeed for the existing conditions. The dot and arrow represents the aircraft. The triangle indicates the condition required to obtain maximum range and the square indicates the maximum endurance condition. This display is used to obtain maximum range or endurance flight or to properly control the airplane during landings or degraded mode engine-out conditions.

Utilization of the Autopilot by IIPACS/IMS tends to be limited to certain modes and certain control features. There appears to be connection to the Autopilot in the minimum energy mode only. The control appears to be limited to attitude and heading. Throttle is still under pilot control.

2.3.4. IIPACS/IMS Critique

The IIPACS/IMS systems are improvements over conventional energy management systems. The airborne computer aids the pilot in making the decision on what control movements are needed for optimal flight paths and in showing how close the aircraft energy state is to unsafe conditions. Even if the computations are not truly optimal or real time they are more accurate than the pilot's intuition for what is optimal or safe. The energy management connection to the Autopilot has the capability of relieving the pilot of the tracking task necessary to maintain a flight mode.

The displays of graphical data and command bars relative to energy management are aids not available in the conventional system. At

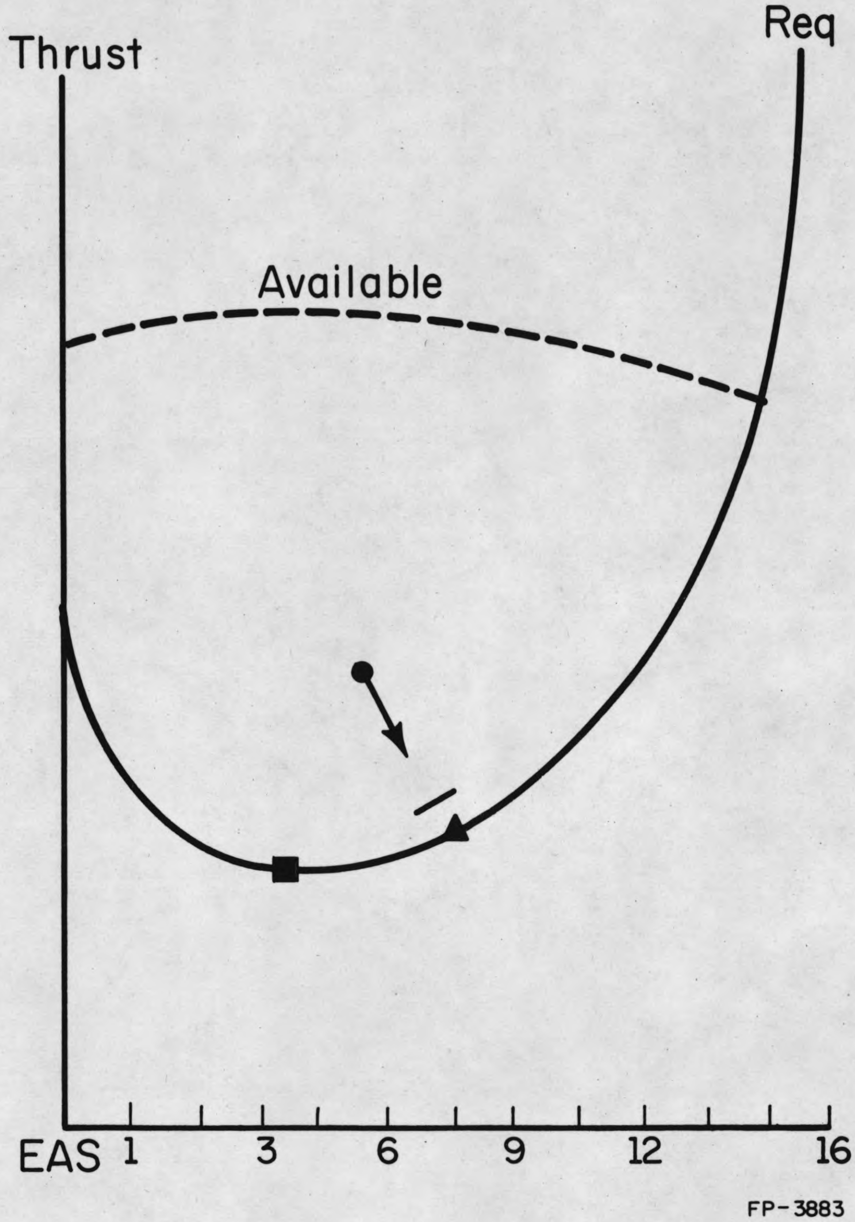

Figure 4. Thrust vs. Airspeed Envelope Display

a glance the pilot obtains information on how close to a trajectory or a dangerous mode of flight he is. The command bars require no decisions by the pilot on how much his control movements should lead the aircraft to prevent overshooting a selected profile. A large class of raw data does not have to be monitored by the pilot except when absolutely needed.

2.3.5. Problems

Improvement is needed on the real time computation capability of the airborne computer. The pilot must fall back on his experience during modes where the computer cannot provide the needed information. Since the ability to be real time probably has meant compromises on a calculation of the true optimal paths or energy states, improved hardware that does allow true optimal calculations would be an improvement. In IIPACS, the modes presented are valid for one or two dimensions only and the situation actually involves more dimensions.

Some displays require interpretation by the pilot as to which control movements are necessary to bring the aircraft state to the desired point. Making command bars available would reduce pilot workload. Allowing the energy management system to have further control of the Autopilot would make possible more complete automation. This also requires constant computer monitoring of commands sent to the Autopilot to be sure that aircraft loading or overall mission success is not compromised. If modes desired are conflicting the computer can offer as a compromise a set of commands that allows some gains from the modes to be realized rather than allowing only one mode at a time. If a clear priority of one mode is necessary then the computer should allow only that mode. The system should allow pilot override of the Autopilot with appropriate feedback, such as control feel, warning the pilot that optimization is being sacrificed.

The energy management system offers a storehouse of information which can be brought to bear against decisions the pilot must make. By showing what the aircraft energy state would be at the completion of different modes the pilot can see what the tradeoffs are. If a computer is required to make high level mission decisions the energy management system can input information to that decision-making computer.

2.4. Navigation

2.4.1. Introduction

On modern jet aircraft, navigation and Autopilot subsystems to augment the pilot's skills are absolutely essential. The functions of such systems include control of the aircraft air surfaces, heading calculation, course corrections, and navigational equipment fault detection.

The primary functions of an Autopilot are to accept from some source (the pilot or navigation system) the desired heading, speed and rate of climb and use this information to actuate the systems for operation of the control surfaces. For convenience the Autopilot should be able to accept changes in single inputs as well as complete changes of all inputs. An Autopilot may also include automatic takeoff and landing capabilities. In addition, systems for stability augmentation and center of gravity control must be either included in the Autopilot subsystem or be in direct communication with this subsystem.

The exact form of the heading data to the Autopilot is dictated by the complexities of the navigation system and Autopilot, although it is always a velocity vector specifying speed and direction in three space. The Autopilot does not keep track of the aircraft's current position.

Automatic takeoff and landing abilities are important in poor visibility situations and will have significant benefits in terms of safety in the near future. These systems are designed to home into the runway by following a directional short range radio transmission. As the aircraft deviates from the required glide path the radio signal changes to indicate the need for a course correction. If the aircraft system does not respond to the corrections the way a faster than real time model of the system does and the deviation is of significant magnitude a failure condition is detected and contingency plans are put into effect. It is now very expensive to add these capabilities to conventional aircraft, but if an aircraft already includes on-board computers and integrated avionics systems, the additional cost of adding these capabilities may not be very high. (see Section 2.1.5.)

Center of gravity control is necessary to maintain aircraft maneuverability. The primary way of affecting the center of gravity is by properly distributing aircraft fuel, the pumping of fuel between various tanks should be done under the command of the Autopilot.

A navigation system is needed to monitor current aircraft state, calculate deviation from the aircraft's prescribed state trajectory, and initiate the proper maneuvers to minimize these deviations. A good system should monitor pilot (or other system manager) requests and determine whether the requests are possible to perform given the overall mission constraints. In addition to following a prescribed state trajectory, the good navigation system will be able to make temporary deviations from the set course to avoid obstacles detected in flight which were unforeseen but moving in a predictable manner. Examples of such obstacles are severe weather systems and other aircraft.

The navigation system may use a wide variety of different position, velocity, and acceleration sensing devices. Among these are the inertial platform, satellite link, ground based radio link, Doppler radar, ground communications through the pilot, altimeter, rate of climb indicator, and airspeed indicator. Each of these gives information for navigational calculations to varying degrees of accuracy. The most accurate is usually the satellite link, but because this depends on radio transmission the most important navigational aid is the inertial platform. The platform is totally self-contained within the aircraft so it is not too dependent on outside conditions. The inertial platform is not a direct indicator of position; rather it calculates position by integrating the forces and torques on a gyroscope caused by aircraft movement. The platform must therefore be updated by the satellite link or ground based radio link to maintain long time accuracy. Indicators such as the altimeter and the airspeed indicator are relatively inaccurate, but they are useful in checking data received from more reliable sources such as the inertial platform, Doppler radar, and/or ground based radio link.

Some method for determining the most accurate navigational data is necessary. Many systems use the Kalman optimal filter technique to estimate an accurate system state. However, to increase long time accuracy it is also necessary to determine if particular sensors are regularly displaying large deviations from the calculated estimations. If this condition exists the sensor is probably faulty, and the system should completely ignore it. Exactly what "regularly" means depends on the instrument in question.

In response to pilot or other system manager requests the navigational system should indicate the results of the requests and suggest alternatives for dealing with hazardous conditions that arise. The navigation system should be in communication with the fuel management system to determine if the aircraft has the fuel to carry out the trajectory requested. Knowledge of the terrain is important so that requests can be checked for possible collisions and so that the system can display helpful navigation maps or other navigation aids. The navigation system should be informed of damage to the aircraft so that estimates of structural and electrical integrity can be included in the evaluation of maneuver and destination requests.

The navigation system should supplement its knowledge of the current terrain below the aircraft through communication with obstacle detection systems, most notably the pilot and the radar system. If an obstacle displays smooth movement or the object is stationary, the navigation system should be able to plot an optimal trajectory around the obstacle automatically. Such a feature is not intended to be particularly useful in evading other man-controlled devices capable of executing complex maneuvers. In general, automatic detection of obstacles from radar inputs is an extremely difficult task and warrants a good deal of independent research.

2.4.2. The IIPACS Autopilot and Navigation System

The IIPACS Autopilot couples the pilot and the navigation system to the physical controls of the aircraft. As an aid to pilot control, the system may be operated through six pilot selected (and deselected) Autopilot modes. These are:

1) Control stick steer--Autopilot has control of stick.
2) Navigation steer--navigation system supplies all commands.
3) Speed control--speed is keyed and held constant.
4) Altitude hold--altitude is keyed and held constant.
5) Automatic terrain following--displacement from ground set and held.
6) Automatic wing sweep--sweep angle is automatically set as a function of speed.

In addition to these functions the autopilot continuously monitors and effects changes in the aircraft stability. As modes are selected and deselected the center of gravity and stability parameters of the aircraft are modified to be consistent with the mode of automatic control specified.

Autopilot malfunctions are displayed via "bingo" lights. The vertical situation display (VSD) is used for pilot queues such as the roll index, roll attitude, yaw deflection, and pitch reference under normal conditions. When flying in terrain following mode the VSD is also used to pictorially display information for aircraft orientation with respect to the ground. Figure 1 shows this display. Altitude, thrust, airspeed, and climb rate are indicated by bargraph displays.

The primary function of the navigational system is to provide enroute navigation information and fly the aircraft to the destination. The navigational system described in the IIPACS manuals is comprised of three basic subsystems--Doppler radar, inertial platform, and satellite. These are augmented with ground map radar, radio data link, and ground radio location systems (direct ranging radio systems). A back up simplified inertial system is provided for degraded mode navigation.

The IIPACS navigational system uses a Kalman optimal estimation technique for making estimates of the aircraft state from a myriad of redundant sensors. The satellite is the preferred navigation aid and is capable of direct positional feedback if the navigational system can reach 4 different satellites (3 satellites determine latitude and longitude, the fourth altitude). The most frequently used system is the inertial platform. The inertial system is periodically updated by the most accurate estimation available of current position of the aircraft (the output from the estimation routines). The Loran and Omega hyperbolic radio systems are preferred over the direct ranging radio systems (TACAN, VORTAC, etc.) because they do not depend as heavily on complex ground based equipment close to the area of aircraft operation. (See Figure 5.)

The hierarchy of navigation system configurations is as follows: (listed in order of confidence)

1) Navigational satellite

2) Doppler radar, inertial platform, ground map radar

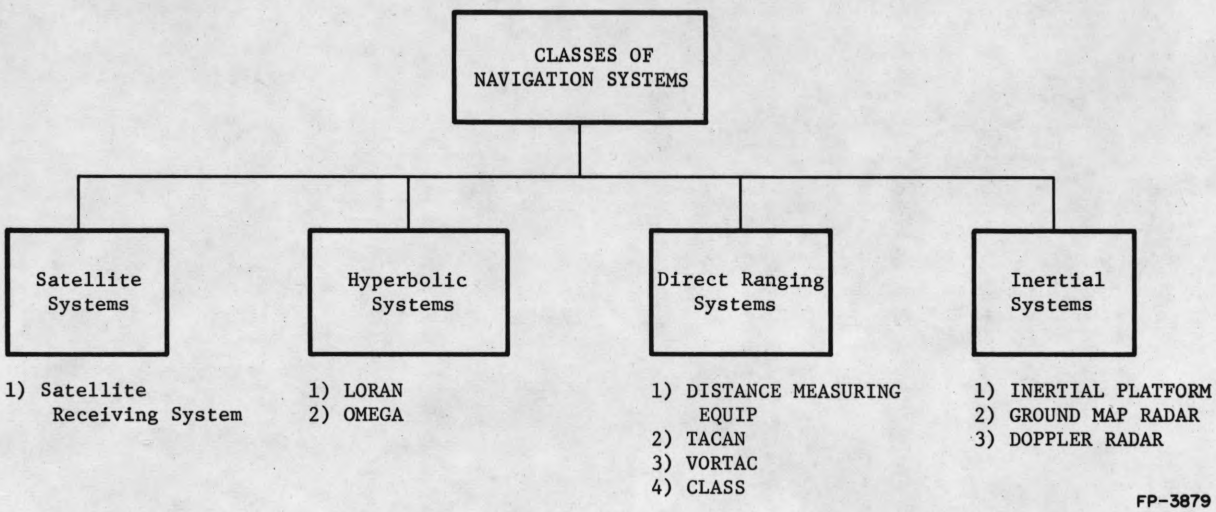

Figure 5. Classes of Navigation System

3) Doppler radar, inertial platform, direct range radio

4) Free inertial, ground map radar

5) Free inertial, direct range radio

6) Free inertial

7) Ground map radar with heading information

8) Direct range radio with heading information

9) Doppler radar, air data--airspeed, altimeter, etc.

10) Air data--air data dead reckoning

Navigation satellite failure causes reliance on the Doppler radar and radio nav updated inertial system. On inertial system failure the navigation system uses Doppler radar and radio nav data. As the best equipment in the system ceases to function the system reverts to more primitive forms of navigation. If all else fails, the system reverts to air data dead reckoning. A system block diagram is shown in Figure 6.

Navigation ground map information is shown as contours on the horizontal situation display (HSD) to augment traditional radar displays. Other information such as headings, altitudes, latitudes, longitudes, and radio station frequencies are shown on special purpose alphanumeric displays. As an additional aid, landing queues are shown on the VSD and a multipurpose display. The VSD shows a line drawing of how the landing approach should look through the aircraft cockpit window. The multipurpose display shows the same situation from a side view.

The Autopilot described in this study is flexible, but because of the way this flexibility was achieved it is quite easy to misuse the Autopilot controls. In a high workload situation the pilot might easily

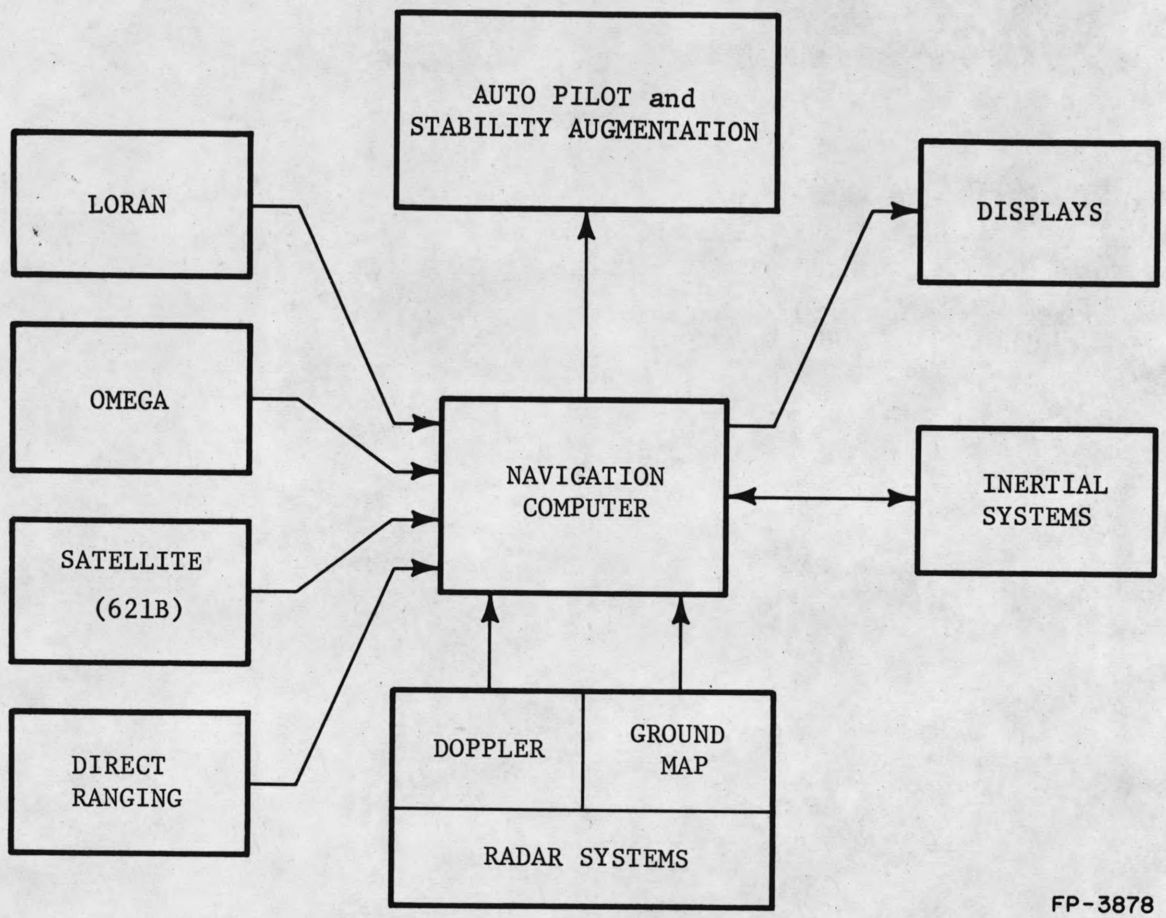

Figure 6. IIPACS Navigation Computer Block Diagram

key in incompatible mode specifications. The last set of mutually compatible modes will be the ones selected. This could mean that a busy pilot might not notice the error until he attempted an emergency maneuver. This type of problem could be partially solved by redefining modes so there are no such contradictory commands. The problem with this approach is that either we cut down on the flexibility of the Autopilot or we increase the already large number of keys which the pilot must remember.

The IIPACS study is primarily concerned with information display for the navigation function even though there is a link between the navigation section and the Autopilot. The IIPACS navigational aids displays are quite good and should be part of any automated system of this kind. However, the total system is much more helpful to the pilot in cases where a mission goes according to plan than where it deviates from the plan. Unfortunately, this means that the pilot gets aid in low workload situations, but little relief in high workload cases. As an example, in a degraded mode situation, the flight models may no longer apply, and so intact portions of the navigation system may no longer be useful.

2.4.3. The IMS Navigation System

This study treats navigation calculations with greater depth, but has postulated approximately the same type of system as the IIPACS study. Kalman optimal filtering is again used to estimate the aircraft state from Doppler radar, Loran radio, Tacan radio, search radar, air data, and inertial guidance. One major difference is that this study does not examine the possibility of satellite navigation systems. Inertial navigation is therefore this system's primary navigational aid. The calculation of navigation data is emphasized because the IMS study deals with the specification of an avionics central processor.

2.5. Degraded Mode Operations

2.5.1. Introduction

The objective of degraded mode analysis and operation is two-fold: to automatically identify failures and their nature, and to reduce the workload of the pilot during critical periods in flight. We emphasize the importance of computer-aided decision-making during high workload situations.

In fact, failure recognition is one of the most difficult aspects of any proposed automatic flight control system for an airplane; certain problems can only be recognized by comparing several parameters, each of which may by itself appear normal.

2.5.2. Conventional Approach

One of the major responsibilities of the pilot in a conventional aircraft is to constantly monitor the flight information and maintain the proper operation of the aircraft. Due to the overwhelming amount of information available at any given time, the pilot must sort, search, and integrate the information in a systemized manner. In conventional aircraft, there appears to be no systematic way of even displaying this information to the pilot in an integrated fashion; the pilot must make all decisions requiring intelligence.

2.5.3. General Description of Problem

2.5.3.1. IIPACS Goals

IIPACS dedicated an entire volume (Vol. III) of its study to degraded mode analysis. In that volume different kinds of failures during various aspects of the mission are documented along with the corrective procedures. Whenever a failure occurs, the major emphasis is on warning the pilot and then supplying him with preprogrammed emergency operations. The system only displays information appropriate to the given emergency so as not to increase the pilot's workload by having him search through irrelevant material.

2.5.3.2. IIPACS Implementation

IIPACS Volume III classifies flight system information requirements according to specific degraded modes. Thus it becomes possible for the pilot to concentrate on a small subset of the total information and controls available when a failure occurs.

However, IIPACS often leaves critical decisions up to the pilot. For example, during takeoff the pilot must recognize an engine failure prior to reaching the single engine control speed (VI), although the designers of IIPACS considered the alternative of letting the system do the recognizing. Thus, if the pilot detects an engine out situation prior to VI, he must press an abort switch which will automatically initiate abort procedures, such as actuating the thrust reversers and wheel brakes.

2.5.4. Critique

2.5.4.1. Improvements Over Conventional System

The IIPACS document provides an extensive top-down analysis of the various failures and the procedures for correcting them. As an example of top-down organization, under the general heading of "Landing Gear Failure" there appear various subheadings such as "During Takeoff" or "During Landing." At the lowest levels are the detection and correction tasks necessary to cope with these failures. Some of these tasks are assigned to man, while other to machine (the IIPACS computer system).

The old problem of pilot fixation is also lessened somewhat. For example, if the pilot is performing a routine maneuver while monitoring one of his displays, any emergency situation automatically detected by IIPACS causes some displays to change, hopefully getting the pilot's attention.

2.5.4.2. Areas of No-Change

The IIPACS philosophy is that the pilot is responsible for detecting most failures from audio and visual input or from the "feel of the plane." To an experienced pilot an engine failure has certain characteristics such as a decrease in noise level in the cockpit or lack of thrust. Whenever the pilot detects a failure, he is expected to look at the display panels for indications of failure, and push the appropriate buttons to initiate corrective procedures.

The pilot's workload is only superficially decreased, for during a high workload period he still must make decisions imposed upon him by the lack of flexibility and the lack of automatic failure detection. As an example, suppose an emergency occurs which the pilot still must detect. He may be concentrating on some other flight aspect (such as getting the landing gear down). In doing so, his attention may be fixed on the display showing the gear's position.

The chief criticism is that the IIPACS study does not supply a good way of automatically detecting and identifying specific failures. Hence one cannot fully utilize the failure mode operations described in the IIPACS document.

2.5.4.3. Drawbacks of the IIPACS System

Pilots who were trained on conventional equipment may find it more difficult to fly an IIPACS equipped aircraft than those who were not; emergency procedures often call for an immediate conditioned response quite different from that expected in a conventional airplane.

2.5.5. Guide to Future Actions

The IIPACS system does not cope adequately with the problem of multiple failures, and the system still requires the pilot to do much of the failure detection. Both of these problems can be attacked by a system which uses bottom-up analysis for failure detection. A flow chart embodying this kind of analysis begins with the basic sensors and then works up, describing the various deductions that may be made based on these sensors. These deductions are then combined to make still higher level deduction until the system identifies failures which can trigger top-down correction procedures. With this approach, techniques for automatically handling multiple failures can be developed.

It is true that such a bottom-up analysis appears to be extremely difficult to write, let alone implement. Furthermore, the number of deductions will combinatorially increase if one considers a "reasonable" number of multiple failures. It is precisely in cases like this where concepts of artificial intelligence are relevant. The balance of this section will give examples of how an intelligent airborne computer system would function. In principle, this computer will monitor the sensors and then employ the data obtained from the sensors to detect one or more failures.

Let us show how the workload can be shifted from the pilot to a computer. A computer can monitor the various sensors and then perform "intelligent" deductions. For instance, a rapid increase in temperature and pressure (thus implying a rapid decrease in elevation) indicates a diving situation, whereas drastic changes in G-force may indicate evasive maneuvers and an intelligent system could deduce that these situations existed. Since the computer can monitor the various sensors much faster than a man can, it can perform high workload tasks such as coping with multiple failures.

Naturally, in an ideal system the pilot should be informed of any failure whenever practical and should, whenever possible, be permitted to take any corrective action. The system should not make any key decisions on its own unless the pilot is already involved in some high workload function such as takeoff maneuvering or responding to another, more critical, failure. The various airplane components (engine, control surfaces, instruments, etc.) can be assigned priority numbers in the sense that a higher number would be assigned in the more critical cases where the pilot should be informed so he can take action. Thus, failure of less critical components occurring at the same time as an engine fire could be handled automatically and then reported back to the pilot as soon as he responded to the fire.

An intelligent system can provide greater effective redundancy. For example, a computer can detect failure of one altitude reporting device if it does not conform within the range predicted by two or more other such devices or their past histories, even though the devices may be quite dissimilar in concept and operation (examples: barometric and radar altimeters). As another example, an airplane component such as an engine or aileron may fail; in such a case, abnormal behavior in most of the instruments monitoring the engine or aileron could cause the computer to recognize the situation.

There are other ways in which the man-machine interaction can be improved. First, the pilot should be able to report any pilot-detected failures in components to the computer system; reporting these failures would then help the system do a better job in monitoring the remaining components that still work. Second, certain very critical decision points during a flight, such as reaching the minimum single-engine control speed, should be reported to the pilot at all times during takeoff runs. This would help the pilot make better decisions in the event of trouble, or make them in a shorter amount of time.

2.6. Weapon Delivery

2.6.1. Introduction

Weapon delivery is probably the single most important function performed by the fighter aircraft. In order to insure the destruction of the target the aircraft must have the capability of supporting a large number of weapons of widely differing types and characteristics. The aircraft system must be able to select arming, fusing, and delivery options for each of the many weapons on board. Some of the weapons are unguided and the weapon impact point is determined by the aircraft trajectory at the time of release. Other weapons are guided but the aircraft trajectory must be controlled so that the weapon can acquire and lock on to its target before release. As a result, during weapon delivery, the flight path of the aircraft must be precisely controlled to insure that the weapon will impact the desired target. To accomplish this the aircraft system must accurately know its own position and velocity relative to the target and must be able to calculate the trajectory the weapon will follow. This implies strong coupling between the flight control system, navigation system, energy management system, target acquisition sensors, and routines to calculate trajectories. In Addition to normal release of weapons the aircraft must be able to safely jettison weapons in an emergency.

2.6.2. What is Provided by IIPACS

The stores management provides integrated selection, control, monitoring, and release of all weapons as well as interfacing with the rest of the avionics system. This is accomplished by use of a master keyboard which is shared with all other avionics functions, the stores/gun select panel which is dedicated to weapons control, a multipurpose display, and an emergency jettison button.

A logic plug is installed at the stores/aircraft interface by the weapons mechanic when the store is loaded. This logic plug supplies the computer with information describing the type and location of all weapons onboard. This information is displayed on the lighted switches on the stores/gun select panel. Arming, fusing, and delivery options are presented on the MPD and are selected through the master keyboard.

2.6.3. Critique of IIPACS

Preparation of a weapon for delivery requires extensive interaction between the pilot and the aircraft system. The pilot must first press the weapon management button to configure the master keyboard for stores management. The stores select panel displays the type and status of each remaining weapon. The pilot presses one or more buttons on the stores select panel to select weapons based on his knowledge of the target. The MPD displays the fusing, sequencing and delivery options for the selected weapon. The pilot selects the desired options using the master keyboard, and the lights on the stores select panel display the selected options. Before release the weapon must be armed using the master arm switch.

To attempt to reduce the workload on the pilot during a combat situation the aircraft system might be allowed to perform the selection tasks. The sequence of events would be as follows: the pilot would designate a target on the horizontal or vertical situation displays.

The system would lock onto the target and examine radar, optical, and infrared data about the target. Based on the relative strengths of the radar, optical, and infrared signals and the altitude, range and relative velocity of the target, the system would select the optimum weapon and options from the remaining stores and display the selection to the pilot. The pilot would approve or disapprove the selection. If disapproved the pilot would have to ask for the second choice of weapons or select the weapon and options himself. If approved the pilot would only have to arm the weapon before release. In this way the number of interactions between the pilot and the system is reduced.

2.7. General Comments

2.7.1. Computer System

One problem common to all the current avionics packages is the lack of a functionally centralized computer facility. This central system should provide:

a) A hardware communication route between every computing unit and every transducer and activator. It may appear obvious, but it must be noted nevertheless that there is nothing to talk about if the hardware link does not exist. This means, as the IMS study has realized, that while many CPUs may be used, each one should be able to perform any critical function. For example, in the IMS system the computing task of the radar system may be done in the central CPUs rather than the specialized radar computer if necessary.

b) A software system that is not designed in a "separate box" fashion as much of IIPACS/IMS is. While the separate box approach does make writing of each subroutine easier, the resulting system is much too inflexible. In an intelligent system, each function must be able to communicate at a high level with other functions, and have some model of what the other functions do. For many tasks it is not possible to do straight line coding to test for all possibilities, instead one must operate with a continuously changing global model of what a function is required to do.

Another area where greater sophistication is needed is in computer handling of failures -- a situation of high pilot workload. It seems possible to go further than IIPACS has in the automatic handling of failures. In many cases, IIPACS gets as far as warning the pilot of the failure and perhaps presenting him with a list of actions, but it does not carry out the actions. In the IIPACS system there are several possible reasons why this is true:

1) The computer cannot decide which of several actions to take because it is inadequately programmed.
2) It cannot decide because some of the information necessary to make a decision can only be obtained by transfer through the pilot.
3) The actions to take are clear but there is no way to initiate the actions.
4) It is felt the pilot must okay the actions.

There is also the further problem, not well treated in IIPACS, of multiple failures. It is clear that a simple fixed priority scheme is insufficient. Which failure is the most important will heavily depend on the current situation.

We feel that what has always been missing from avionics software is a good operating system. It is not easy to design a system that allows fast and easy access to system resources by many requesting sources, and is also able to lock out some requesters when necessary. This is not simple timesharing, due to the importance of hardware and software failures. It is necessary to be able to recognize when some module has gone beserk and ignore it. In situations where several sources of the same information are available, the module requesting information should have some idea of what failures are likely and which source is more reliable.

To illustrate how far there is to go in the design of airborne operating systems, consider the following description of current systems:

> Most present airborne computers use a main program to connect and to sequence the execution of programs. The main program is a loop with a fixed sequence of execution for the programs, even though the execution of any given program may consist of only a test which causes the rest of the program to be skipped. Most of the major branching resulting from program tests is determined by the pilot or navigator who uses panel switches to select equipment, modes, or functions he wishes to use. While the computer may calculate some of its own branching, and while abrupt branching may occur as the result of hardware interrupts, most of the main program task is to loop through the computer programs in a sequence set by the pilot or navigator. The main program loop is designed to meet the computational speed requirements of each computer function in the worst case (heaviest computer loading) although the computer often will not be executing the worst case.

The IMS study then goes on to describe their proposed operating system. It breaks the mission up into "events" and the computing jobs into "tasks" which are run when called by individual task monitors. While the IMS operating system (IMSOS) is a good step forward, it still contains features which will make it difficult for programs running under it to interact freely.

In both the IIPACS and IMS studies, it was found necessary to explicitly "segmentize" the mission within the computer. This makes program sequencing easier, but also forces the consideration of failures to be a detached, special case. The following quote cites a typical problem this segmentizing can introduce:

> The basis for the IMSOS scheduling is a preflight mission plan that is revisable enroute. It is believed that the problem of the computer's becoming "lost" in following the mission plan can be minimized by special enroute programmed checks, at worst, a temporary degradation to manual mode would occur.

2.7.2. Pilot Workload

This is some indication that the information displayed to pilot in the IIPACS system can be so prolific that it could be very difficult to use. Two quotes from IIPACS study, Vol. 1, Appendix III, page 123, the section listing the evaluations given about the IIPACS mock-up cockpit by veteran military pilots, support this contention:

> I am afraid that the amount of information being displayed is too much. If this amount of information is required, then we need another seat in this airplane.
>
> (The IIPACS displays) may be too distracting to be of useful value. (They) display too much information?

The only viable solution to the information "explosion" problem is to display less information. To do this without degrading the pilot/aircraft system it is necessary for intelligent avionics software to order this information for pilot attention according to a dynamic priority scheme that gives the pilot exactly what he needs when he needs it and acts on much of the data by itself. This type of software can be arrived at only interrelating each system module into cooperating processes, and giving the system some ability and responsibility for decision-making.

3. GENERAL APPRAISAL AND SUGGESTIONS FOR IMPROVEMENT

3.1. Introduction

This section presents a number of important ideas. It is divided into three sections:

3.2. A summary of the main improvements and main difficulties in the IIPACS/IMS systems with respect to pilot workload;

3.3. A similar assessment with respect to system reliability and safety; and

3.4. Specific suggestions for improvement of these systems.

This section refers roughly to the situation where the IIPACS system is added to a single-man aircraft. If the IIPACS system replaces one man in a two-man aircraft, then the shortcomings become more serious.

3.2. Pilot Workload with IIPACS/IMS

3.2.1. Improvements in Pilot Workload

(1) The IIPACS system Autopilot will allow the pilot to select more modes than currently available in aircraft. These modes should increase the level of aircraft performance given the same amount of pilot workload, or reduce the required pilot workload to achieve the same level of aircraft performance. In addition, some stability augmentation is always done by the system, which will reduce pilot workload.

(2) The guidance system should also offer the same type of improvement, i.e. increased performance given the same workload, or decreased workload to achieve the same performance level.

(3) Some kinds of data will be presented in a more useable or concise form. Thus the pilot will not have to do calculations in his

head given the raw data, but can get the computed data directly. Similarly, the pilot should not have to perform as many comparisons with memorized numbers, but should be more easily able to obtain the results of such comparisons directly.

(4) The pilot will be able to be a little less involved in his instruments, since certain problem situations will be automatically detected by the system and brought to his attention. The decrease in workload will be fairly small, however, since most failures still must be detected by the pilot, and more seriously, the system in general does not warn of impeding problems but only of problems that already exist. Thus the pilot must still monitor the instruments to about the same degree as in conventional aircraft.

3.2.2. Negative Changes in Pilot Workload

(1) In cases where the pilot has to read text from a screen (i.e. in order to read an emergency procedure or other stored information) his workload will be higher than if he had memorized the information. While text is a very general way of presenting data, such data takes much longer to grasp than does graphic data.

(2) If the pilot wishes to know information that is not currently displayed, he must key in the request, whereas in conventional aircraft the information is always directly available and the pilot need only remember where to look.

(3) In a conventional aircraft, the pilot knows the meaning of each instrument from its position. In the IIPACS system, he must either read some text or recognize by shape which information is being

displayed. It probably will be difficult to avoid having some displays look quite similar.

(4) All these workload problems will be especially acute for a pilot trained originally on aircraft not equipped with IIPACS. Such a pilot must modify his old reactions and routines, and thus may spend more time deciding what to do. Given the fact that workload decreases are modest at best, such a pilot might in fact end up with a higher workload.

3.2.3. Areas with Little or No change in Workload

(1) Unfortunately the IIPACS system improvements in workload seem to apply almost exclusively to the situations where workload was low anyhow. Virtually nothing has been done to relieve the pilot during emergencies, take-offs and landings, or combat maneuvers.

(2) The pilot must still implement all decisions and most controls that he does in a conventional aircraft. The designers of the IIPACS system apparently did not trust a computer to take over even the most routine decision making functions of the pilot.

(3) Much of the failure detection, especially of impending failures, must still be done by the pilot, and once a failure is detected, the pilot must cope with the situation by himself.

3.3. System Reliability and Safety

3.3.1. Improvements in Reliability and Safety

(1) The possibility of a pilot being unaware of certain emergency situations is considerably lessened. Any problems identified by the system are signalled by changes in the main displays, so there is little chance that the pilot will fail to become aware of such problems.

(2) Since emergency procedures can be displayed by the system, there is less chance that the pilot will act incorrectly.

(3) Automatic stability augmentation should prevent certain emergencies, for example a situation where the pilot cannot perform a desired maneuver because his center of gravity is badly placed.

(4) The accuracy of the aircraft guidance system should improve, and its reliability should be greater.

(5) The ability to optimize some flight paths should give the aircraft a distinct performance edge over conventional aircraft whenever such optimization is possible. Obviously this can mean that the pilot in an IIPACS equipped aircraft will survive in some cases where a pilot in a conventional aircraft would not.

3.3.2. Decreases in Aircraft Reliability and Safety

(1) In an emergency the pilot must perform virtually all the functions he does in a conventional aircraft, but he must perform them in a different manner. For a pilot trained on a conventional plane, this could be a serious safety hazard, since the pilot's basic emergency reactions must be changed. Of course, in some sense this is a problem whenever any change is made in a man-machine system.

(2) There should be a set of conventional instruments available to allow flight even if the display system should fail. (This omission has been corrected in the DAIS system).

(3) It is possible that in the IIPACS aircraft, a pilot might fail to detect a faulty sensor that he might have noticed in a conventional aircraft due to abnormal or erratic instrument motion.

(4) There may be some danger in a pilot's reliance on situation displays that are not updated in real time. According to all the information we could find, some IIPACS displays will not be updated in real time. One specific example is the energy management display which will not be realtime during air-to-air combat or landing maneuvers. (see page 111, volume 4).

(5) In our estimation, the IIPACS feature which changes the loop gain between the control stick and control surfaces should not be implemented as described. As far as we can tell from the IIPACS manuals, the system eliminates all tactile feedback, which in conventional aircraft provides indispensible indications about dangerous situations such as impeding stall or excessive G-loading. The amount of feedback could be varied by the pilot, but he should have some choice in the matter.

3.3.3. Areas of No Change in Safety or Reliability

(1) While the systems described will not allow an emergency to go unnoticed, in general they do not help very much in avoiding the emergency situation to begin with. Since all corrective control actions must be by the pilot, the IIPACS designers realized that it would be dangerously distracting to sound alarms or switch displays whenever a parameter gets close to a danger area. As long as the pilot is tied to the equivalent of a conventional instrument scan, the system's threshold of sensitivity to danger cannot be set very low.

(2) Once the system has notified the pilot of an emergency situation, it does very little more to alleviate the pilot's workload or to help correct the emergency.

(3) Significantly, the data displayed to the pilot is no more reliable than in a conventional aircraft. It is easy to design a computer system with redundant sensors and display the majority decision. This is not possible in a conventional plane since there is not space for three instruments of each type, and no way for the pilot to monitor three sets of instruments. We mention this as one of a number of fairly obvious additions one would expect on an aircraft with an on-board computer.

3.4. Specific Suggestions for Improvements at the IIPACS/IMS Level of Automation

3.4.1. Display Priorities

A more intelligent system should be included to run the display. In particular the system should have provisions for multiple failures with prearranged priorities so that the most critical failure is guaranteed to be displayed. Such a system requires more computer power, but should not be too difficult technically to implement.

3.4.2. Display Content

It is inadequate to only display failures and emergency situations after they have occurred. Impending emergencies should be displayed in time to allow corrective action. As we have noted, however, the pilot already suffers from information overload. In cases where the pilot reads a procedure from the screen and implements it without further decisions, he should be taken out of the control loop totally. We feel that there is no need for the pilot to perform tasks of this nature. Some examples of such tasks include emergency procedures, so that this change should help specifically in high workload situations.

3.4.3. Emergency Mode

There should be a pilot selectable mode in which the computer system will perform as many operations as it can without the pilot's aid. The system may not perform these functions as well as the pilot could, but in situations such as air-to-air combat or multiple emergencies, the pilot may wish to direct as much attention as possible to his specific problems. In such cases the choice may be between suboptimal automatic system action and no action at all, and obviously, the former is preferable.

3.4.4. Instruments

Enough conventional instruments should be available to allow the pilot to fly the aircraft even if all displays should fail.

3.4.5. Automatic Control Gain Changes

The gain and thus the "feel" of the controls should not change except when the pilot specifically requests such change, or when he abdicates his right to know about such changes.

3.4.6. Mode Select

Using current technology, it is possible to have the pilot select a particular point in the energy envelope at which to operate, using a light pen or touch display to indicate the desired operating point. The IIPACS system now offers only modes on the envelope extremes: maximum range, minimum fuel, maximum rate climb, etc.

3.4.7. Real Time Display Updates

A number of techniques can be brought to bear on this problem. One example is prestoring of information combined with table look-up. Techniques like hash-coding and interpolation should allow real time updates of any flight information, given adequate amounts of memory. One of the prime results of early computer work was the demonstration that there is a direct memory size/process speed tradeoff.

3.4.8. Failure Prediction, Detection, and Connection

(1) While it is not possible to have a fully reliable system for failure detection and prediction within IIPACS, much more could be done than the designers have suggested. Small processors could be dedicated to cross-checking system readings and calculations, looking for parameters that are approaching envelope limits, and other tasks. Some care should be taken to choose tasks for these processors which have the greatest effect on relieving the pilot during high workload periods.

(2) Whenever the corrective procedure for a failure is straightforward, the pilot should be relieved of responsibility for performing that procedure. An effort should be made to avoid having pilot tasks which involve reading an instruction from the display screen and mechanically carrying it out.

4. ESSENTIAL CHARACTERISTICS OF A FULLY AUTOMATED SYSTEM AND THE IMPORTANCE OF PROGRAM INTELLIGENCE

4.1. Description of Essential Characteristics of a Fully Automated System

As should be clear by now, there are many possible levels of automation. For instance, for all practical purposes the cruise phase of a mission is already automated to a high degree, at least as long as there are no contingencies. Moreover, even in an aircraft that can fly itself automatically, there are still levels of automation. We can imagine a marginally adequate system or a very reliable one. Thus we must not only consider how much of a system is automated, but how well that system is automated. As long as a man-machine system performs better than a machine only system, the man will of course remain in the control loop during normal circumstances. But during emergencies there would be great value in having a machine which can be asked to perform certain operations independently, even if it does not perform as well as the man-machine system, since these operations may otherwise not be performed at all.

The system described in this section is intended to be a realistic assessment of what could be done in the long run through the application of ideas and concepts from the fields of artificial intelligence and conventional automation. How fast such systems could be realized and how good they would be depends on the degree of funding, the speed at which avionics computers of adequate size become available, pilot acceptance of these systems, and many other factors, including of course the accuracy of our assessment and predication of the situation.

A system which realized even a few of these ideas could be used: (1) to augment the performance and reliability of a single-man aircraft, (2) supply enough functional assistance so that only a single man is required in a normally two-man aircraft at no expense in performance, (3) to make a trainer aircraft safer or (4) to improve the operation of an RPV.

With this preface, we will proceed with the description of a fully automated system:

(1) First and foremost this system will be designed to be able to fly by itself if the pilot requests it to do so, or if the pilot is unable to fly himself. The system will contain provisions for detecting when the pilot has relinquished control. The minimal system will fly directly to a base if the pilot is no longer functioning, avoiding obstacles and weather systems on the way. The system thus will consider the pilot as a component which may also be disabled; however pilot disability will not mean total system failure.

(2) The system will be flexible; it will allow the pilot to do whatever portion of the flying he wishes to do, with the exception that it will not allow him to apply controls that would lead to a crash, stall or other emergency situation unless the pilot first notifies the system that he wishes to be able to exceed the normal safety envelopes (we include obstacles as part of the envelope). There could be several levels of risk the pilot could choose to operate within. If he activates the most dangerous mode, the system would not intervene in any circumstances; at the most conservative level, the system would keep all instruments

within safety areas. Such safety envelopes can be set to allow performance much closer to the true time limits of the plane's potential than is possible when the pilot keeps certain instrument limits in mind as he scans. These scan limits must be conservative in order to keep a reasonable safety margin, whereas a computer system can devote sufficient attention to the aircraft state to allow much closer approaches to the actual limits. A system like this would also be invaluable for trainer aircraft. A trainee could be started in the lowest risk mode, and as he become more proficient could move to modes of greater risk.

(3) Because the aircraft's computer system will not allow the aircraft to crash, stall, etc. except in the highest risk mode, the pilot will be freed from doing an instrument scan, and thus can concentrate on any aspect of flight he chooses. When he approaches system bounds or when emergencies occur, the system will produce a set of options and give the pilot an audio signal or recorded message. In many instances a recorded message could request a yes/no decision or selection of one of several options. If the number of options were small enough, the pilot could designate his choice verbally, or at worst by pressing one of several multipurpose buttons. Thus in these cases his workload could by drastically reduced, since his eyes and hands would for the most part be free to continue with other tasks (we are aware of the difficulties of speech recognition in a noisy cockpit environment).

(4) Another reduction in the pilot's scanning workload is achieved by having zero pressure on the control stick represent tactility to the pilot the case where the system is achieving the currently specified system goal (either prestored or keyed in). If the pilot must apply

pressure to respond to an emergency (i.e. to avoid a missile) then he will have direct feedback that he is deviating from the flight plan, without having to consult his instruments, thus leaving his eyes free to aid in guiding the aircraft. The system could of course return to its goal after such maneuvers. The system will be able to detect failures and reconfigure itself to continue flight without pilot involvement up to the point where it is no longer possible to continue the flight plan unmodified. At this point the system will give the pilot options. The system will notify the pilot of each failure it detects, and will accept and act on information and pilot-detected failures. In light workload phases of flight, the pilot could take part in the reconfiguration if he wished.

(5) System goals are at a higher level than are goals in a current system. Thus for example if the pilot has specified that he wishes to go to a particular set of coordinates, the system will be able to return to that goal after the pilot has executed emergency evasive maneuvers, or flown around a weather system. In contrast, a lower level goal is one like "hold heading" or "hold altitude." If these are the only available modes, then the pilot must recalculate and begin a new heading, a new climb rate, etc. after executing an unexpected deviation from a flight plan.

(6) The plane can respond to instructions from the ground or from another plane, since it will be able to accept high level commands such as "fly from here to point A." Probably it would only accept commands from the ground if the pilot had already relinquished control.

(7) The system will be able to land and take off automatically, even in degraded modes. The model of the aircraft used by the system to predict responses to controls must thus be flexible enough to represent any conceivable state of the aircraft, and there must be systems capable of adapting the model to the actual aircraft state.

4.2. Relevant Concepts of Program Intelligence

Embedded in the previous section are a number of system capabilities which can only be realized by an "intelligent system." By an "intelligent system" we mean one which is able to adapt and respond to the current situation, one which is able to make predictions and decisions within its universe, one which can accept and provide high level information to a user, and one which can remember important information. An intelligent system is thus intelligent with respect to its domain, and not necessarily intelligent in a general sense, as a human being is intelligent.

The field of artificial intelligence has endeavored to understand what is necessary to produce such systems. In the process, a number of concepts have emerged which have proved useful in designing intelligent systems. We will describe a number of the most important concepts below.

4.2.1. System Organization

In order to exhibit intelligence, a system must be organized in an appropriate manner.

(a) The system organization must be an integrated whole; a system made up of a number of independent boxes will not be capable of intelligent action. For example, it is not sufficient to monitor individual instruments in order to decide whether an emergency exists. While some emergencies can be detected in such a manner, many can only be recognized by a system able to detect a dangerous combination of readings, no single one of which may exceed a limit by itself. For another example, many emergencies are detectable only if one can recognize the failure of the aircraft to respond appropriately to control inputs. In order to detect such situations it is also necessary to have a model which predicts proper instrument responses and compares these values with the actual responses. (Individual boxes which can all communicate with each other effectively comprise an integrated system; a system with a central monitor and a number of peripheral subsystems also qualifies.)

(b) The system must be heterarchical, in order to identify the nature of an already detected emergency situation. It is necessary for a system to examine various parameters for evidence concerning the identity of the problem system or systems. As an example, an emergency situation where the aircraft is losing altitude very rapidly may be caused by a number of different subsystem failures, and it is necessary to check other data to determine which subsystem is responsible. A heterarchical system is one organized so that information flows both from lower levels (e.g. instruments) to higher levels (i.e. emergency detection routines) and from higher levels back to lower levels, as well as laterally between subsystems at the same level.

A heterarchical system is necessary in order to automatically realize pilot protocols.

(c) The system must be organized on an interrupt basis. By this we mean that the system cannot operate by running over and over a cyclic list of tests and instructions. Such a system can become fixated on some portion of its processing and not get to a portion of the cycle where an emergency is detected until too late. There must be parallel subsystems capable of gaining the attention of a central processor on a priority interrupt basis.

4.2.2. Procedural Knowledge

One key problem attacked by artificial intelligence is the problem of representing dynamic knowledge. Computers have been used from their beginnings to store numbers as data with programs to operate on the data; this type of data is static and numerical. In artificial intelligence we now are working with concepts that allow programs to operate on and utilize procedural knowledge as data. This means that decision procedures, test procedures, display procedures, etc. can all be stored as if they were data, and can be retrieved, modified and interpreted by other programs. All natural language programs of the past few years have been based primarily on these ideas.

4.2.3. The Representation Problem

The representation problem is the problem of finding just what form procedural data must have in order to be able to effectively store all the knowledge necessary to specify a procedure. The problem has three parts: (1) One must pick a form of representation, e.g. a language in which the knowledge can be expressed: (2) The knowledge must be organized in such a way that it is accessible; and (3) One must make sure that there is sufficient knowledge to adequately specify the procedures.

The process involved in solving the representation problem is often referred to as modelling.

The core of a fully automated system is a procedural model of a pilot. In order to construct such a model one needs a great deal of information about the factors a pilot takes into consideration in making decisions: deciding when a situation is out of the ordinary, deciding how to proceed in pinpointing the nature of problems, deciding the best course of action in a given situation, and so on.

One cannot get enough information to construct such a model from pilot manuals alone, since manuals assume that any person using the manual also has "common sense," manual skills, the ability to look at and understand the world around him, and numerous other abilities. Thus in order to use the knowledge in the manuals these abilities must be added to the system in an appropriate procedural form or through alternative substitutes, or else the system must take into account throughout an inherent lack of certain pilot abilities.

4.2.4. Automatic Programming

It has been usually true in the past that the major part of creating any intelligent system is deciding on the representations to be used by the system. Once representations have been chosen, writing software to generate, modify, and utilize these representations has proved relatively easy. Much current research is focused on finding means to make the choice of representations easier. Such research is a portion of the field called automatic programming; one basic idea is to set up a representation which can then be modified by the user with a small number of commands. The system automatically generates modifications to the representation to reflect all the consequences of the modification.

At another level of sophistication, there is research on programs which write programs according to certain specifications. While such research is still in its beginning phases, it holds the promise of providing techniques far more powerful than those we have today for writing complex programs. Conceivably such programs could be directed by English language commands and could interact with a user, e.g. by asking for additional specifications or information.

4.3. A Possible Configuration For a Fully Automated System

Figure 7 gives an overall view of an automated system, showing how the computer will interact with the remaining components. Except for the "computer system" box, these components are the standard ones currently used in aircraft, although some modifications are expected (such as the IIPACS displays).

Figure 8 gives a more detailed block diagram of the "computer system" box itself (within the dashed lines). The data bank consists of a common memory module available to all of the central processing units (CPU's). In it, various aircraft capabilities and flight characteristics are stored. This bank includes a set of aircraft models which can be used to predict the flight path for the next few minutes. These models can take into account the fact that not all aircraft subsystems (such as engines, ailerons, etc.) may be functional. Also included in the data bank are terrain and map data, energy management tables, various correction

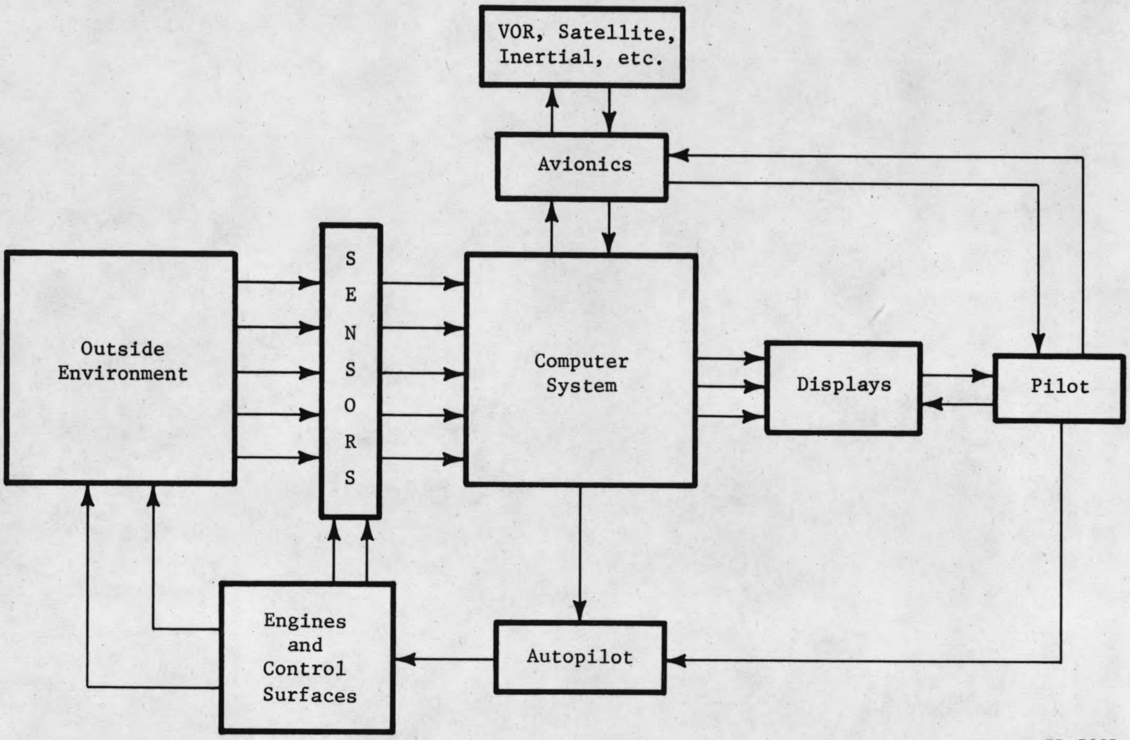

Figure 7. <u>Automated System Block Diagram</u>

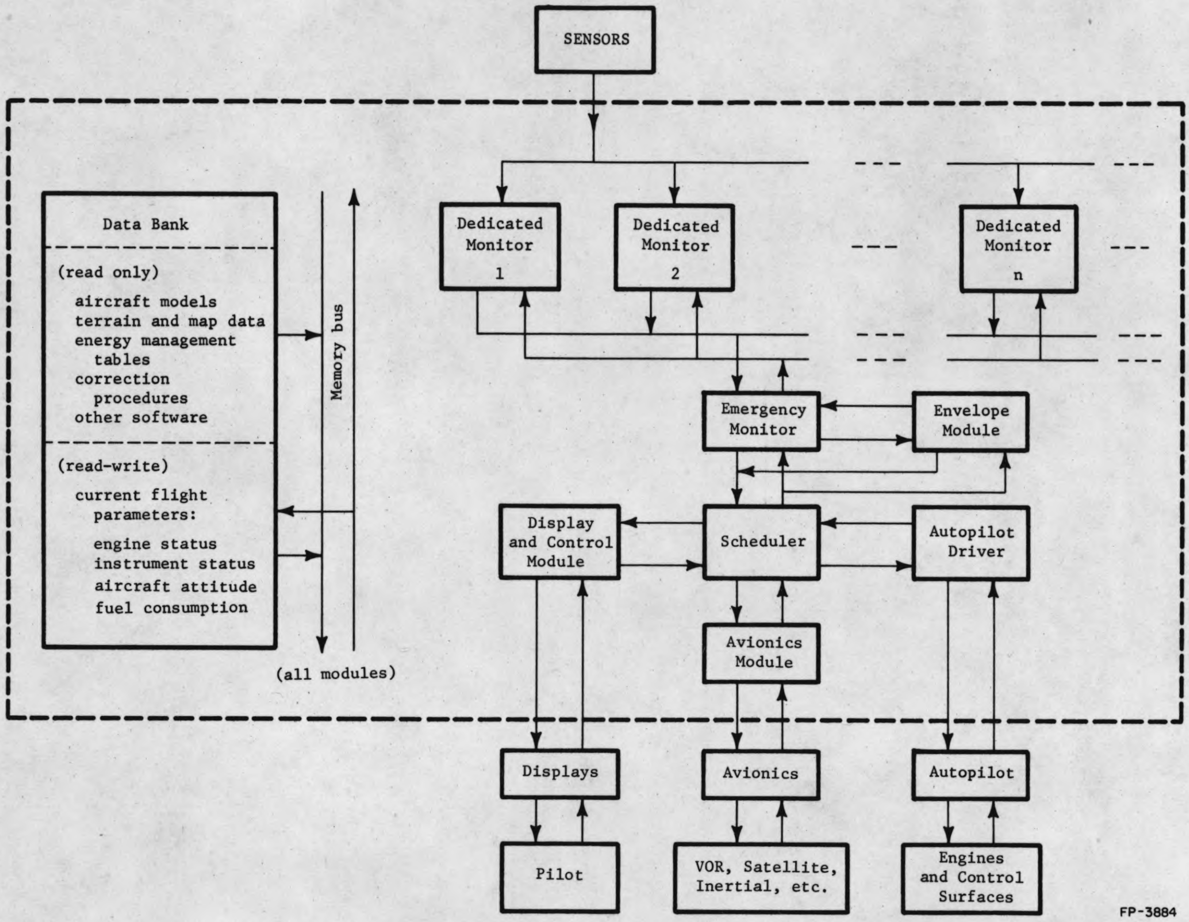

Figure 8. Detailed Diagram of the Computer System Box of Figure 7. All boxes within the dashed lines have access to the data bank.

procedures, and other miscellaneous software.

This data remains constant throughout a flight. To provide additional reliability, it is to be designated as "read-only", which means that accidental erasures cannot occur. The data bank also contains variable data such as the current flight parameters. These include indications of the current status of the engines and instruments, the attitude of the aircraft, the amount of remaining fuel, current fuel consumption rate, and the various operating modes selected by the pilot.

The remaining modules are the various CPU's in the system. Each CPU has its own private memory bank to guarantee fast access to its own programs and variables. The dedicated monitors perform low-level analyses (and resulting deductions) of the sensor data from pressure gauges, fuel-flow meters, wing deicers, combustion temperatures, etc. As an example, one monitor may be dedicated to an engine; it "reads" the sensor data pertaining to that engine and then draws possible conclusions, e.g. everything is O.K., one gauge is malfunctioning, or the engine is on fire.

Emergencies detected by the monitors described above will interrupt the emergency monitor. This module has the task of coordinating the various failures that may occur; it maintains a priority scheme to assist it in case of multiple failures.

The envelope slave computes the flight envelopes and checks to determine whether the current flight path will remain within them. Any "out of envelope" conditions will cause an alarm interrupt of the main CPU (scheduler) so that corrective action can be taken. By "envelope" we mean an extended envelope which also includes the ground and weather systems as constraints on the current flight path.

The Autopilot driver is actually a higher-level Autopilot. It has deductive capabilities, so that it can translate a high-level command like "perform a thirty-degree coordinated turn to the right" into the lower-level commands which it transmits to the Autopilot. In doing so, it takes into consideration the current state of the aircraft (an engine or rudder may be malfunctioning).

The avionics slave not only encodes (decodes) messages transmitted to (received from) the various avionics, but it also supplies control signals to change frequencies, select transponder modes, turn the VOR dial, etc. The displays and control panels are manipulated in very much the same manner by the display and control slave.

It is the scheduler's job to coordinate the other modules. In doing so, it will frequently perform rather sophisticated high-level deductions. As an example, suppose the pilot is just about to exceed the flight envelope. The envelope slave, upon detecting this condition, alarms the scheduler which must in turn notify both the autopilot driver and the display module. Before doing so, the scheduler must first determine the proper maneuver the airplane must take; this is done by examining the data bank along with parameters received from the other modules.

5. CONCLUSION AND RECOMMENDATIONS

5.1. Possible Trends in Advanced Automation for Flight Operations

5.1.1. Introduction

In the following sections we shall attempt to predict some possible trends in advanced automation for flight operations. Although these are nothing but educated guesses they do present a reasonable picture given our knowledge of the present state of the art of automation in aviation and current trends in computer research. The periods identified are operational periods. To obtain development periods subtract 5 from the years. To obtain research periods subtract 10. For example, if according to our prediction, automatic energy management will be operational during the period 1985-1990, development should occur during the years 1980-1985 and research should occur during the years no later than 1975-1980.

In general, tasks in flight operations are highly interrelated, (See Fig. 9) although we shall attempt in the following to identify individual tasks for emphasis. Any workable program may involve at least several items on the list.

5.1.2. 1975-1980: The IIPACS/IMS Years

During this period many of the concepts contained in IIPACS/IMS will be made operational. The pilot will enjoy an information management system and will probably have some form of time-shared display. Some improvements on man-machine communication will take place. These improvements will make IIPACS/IMS more practical and acceptable to most pilots. Situations will still be difficult during high workload periods. The two-man fighter will still outperform the one-man fighter in most instances.

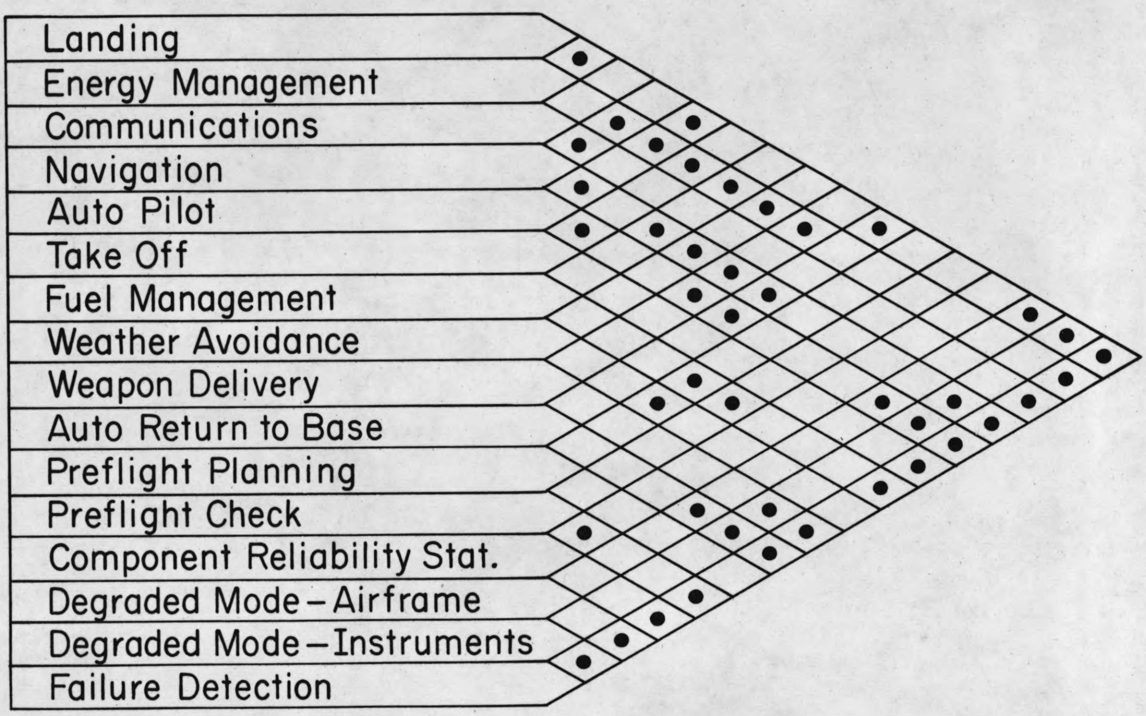

Figure 9. <u>Relationship Between Automated Functions</u>
A dot indicates direct interrelation between areas.

5.1.3. 1980-1985: Years of Intelligent Routines

Key concepts during this period will be:

1. Data Base for Flight History, etc.
2. Pre-Flight Planning and Post-Flight Analysis
3. Extended Navigation, Obstacle Avoidance, and Dynamic Rerouting
4. Automatic Returns to Base (Under favorable conditions)
5. Pseudo-Natural Language Communication
6. System Fault Diagnosis

First to emerge, due primarily to LSI technology, will be large data bases built out of compact and high-density semiconductor memories. These data bases will be the stepping stones to the automatic and routine recording and analysis of flight histories for various purposes including preventive maintenance. Automatic systems can then be built to do pre-flight planning and post-flight analyses. Dynamic rerouting routines can be constructed to avoid obstacles during flight. Coupled with suitable nav aids much of cruising is completely automated. Due to the lack of an accurate pattern recognition capability, the system has to be informed of the potential presence and location of obstacles. Toward the end of this period systems can be constructed for automatic return to base, under favorable conditions. Thus cruising becomes completely routine. Take off and landing are automatically done during most circumstances.

At the same time systems with pseudo-natural language capability are constructed so the pilot does not have to learn computer jargons anymore. In addition, automatic diagnostic routines will be developed for fault isolation and location. Also developed will be automatic recovery routines.

Everything that is mentioned here is within the state of the art. We have the computer know-how to accomplish all these tasks. What needs to be done is a development program to perfect the techniques and design the systems. No new breakthrough in research is required.

5.1.4. 1985-1990: The Emergence of Baseline Intelligent Systems

Key concepts during this period will be:

7. Automatic Failure Detection and Prediction
8. Automatic Degraded Mode Operation
9. Automatic Energy Management
10. Obstacle Avoidance with Recognition
11. Intelligent Man-Machine, Machine-Machine Communication (Including natural language, but no speech)

Tasks listed here are feasible in principle. The present research frontier has touched upon many similar questions. Yet due to lack of detailed understanding and development they remain in the gray region of semi-unknown. Given a concerted effect success is almost guaranteed.

Automatic failure detection is probably the easiest of all tasks. Failure prediction will require recognition techniques, logic, an extensive data base and system model. A suitable data base is also the key to degraded mode operation. Automatic energy management is very straightforward. The major obstacle in automatic energy management is its real-time requirement. It is expected that by 1985 computing power will be so cheap that the real-time requirement can be met by the brute-force approach. Recognition techniques should by now be developed with sufficient power to do natural language communication and automatic